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Numerical Tokamak Turbulence Project

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Research Objectives

The primary research objective of the Numerical Tokamak Turbulence Project (NTTP) is to develop a predictive ability in modeling turbulent transport due to drift-type instabilities in the core of tokamak fusion experiments, through the use of three-dimensional kinetic and fluid simulations and the derivation of reduced models.

Computational Approach

Two main classes of three-dimensional initial-value simulation algorithms, gyrokinetic (GK) and gyro-Landau-fluid (GLF), are being applied to the simulation of tokamak turbulent core transport. The GK simulations are based on (1) particle-in-cell (PIC) methods for the self-consistent solution of Poisson's equation (reduced to a quasi-neutrality relation), Maxwell + Poisson equations in electromagnetic extensions, and plasma equations of motion; and (2) domain decomposition methods to run efficiently in parallel on the T3E and other parallel computers. An electromagnetic, 5-D Eulerian GK code has been developed in the last year and a half that is not particle-based and is noise-free, and whose efficiency and resolution characteristics are being explored. The GLF algorithm is based on an alternative solution of the fundamental GK and quasi-neutrality equations, in which fluid moment equations are solved instead of particle equations. The GLF simulations have been performed on massively parallel computers, particularly the T3E at NERSC. Both flux-tube, i.e., toroidal annulus, and global toroidal GK and GLF simulations are being performed to study tokamak turbulence.

Accomplishments

Significant advances have been realized on both the gyrokinetic and the gyrofluid fronts. Gyrokinetic calculations have been extended to more than one ion species to study the influence of impurity injection on ion temperature gradient (ITG) driven turbulence. These calculations have shown a dramatic reduction in the fluctuation levels and heat conductivity upon injection and have helped elucidate experimental results on DIII-D and TEXTOR which show the same effect. Results from extensive gyrokinetic and gyrofluid calculations of ITG instability have been obtained, tabulated and prepared for publication as part of the Cyclone Project, an outgrowth of the NTTP. These predictions have been compared with tokamak plasma thermal transport models that have been widely used for predicting the performance of the proposed ITER tokamak. These comparisons provide information on effects of differences in the physics content of the various models. Many of the comparisons are undertaken for a simplified plasma model and geometry which is an idealization of the plasma conditions and geometry in a fusion-reactor-relevant experiment in DIII-D. Most of the models show good agreement in their predictions and assumptions for the linear growth rates and frequencies. There are some differences associated with different equilibria. However, there are significant differences in the transport levels between the models. The causes of some of the differences have been examined in some detail, with particular attention to numerical convergence in the turbulence simulations. The gyrokinetic results are giving guidance to other NTTP researchers in improving the closure model(s) in the gyrofluid formalism to obtain better agreement with the gyrokinetic results.

A simple fit for the dependence of the thermal flux on the temperature gradient has been discovered which takes into account the nonlinear upshift of the effective marginal temperature gradient found in FY98, and suggests a considerable simplification in the theoretical picture of toroidal ITG turbulence. The gyrokinetic simulations demonstrated good agreement with the analytical theory of Hinton and Rosenbluth in the role of neoclassical physics in relaxing zonal shear flows. Such shear flows have a profound influence on the steady-state turbulence level. Gyrokinetics simulations with collisions showed how collisions further relax the zonal flows, which in turn leads to a higher level of turbulence, in qualitative agreement with experiments. Gyrokinetic simulations addressing the influence of the scale size of equilibrium temperature and density gradients demonstrated how the results of radially local flux-tube simulations can be approached in the results of simulations in which the length scale of the profile variations is increased, and that profile variations reduce the transport below the local expectation at the radius at which the temperature gradient has its maximum. However, because of the nonlocal character of the turbulence in such cases, the transport at other minor radii can increase relative to the local value.

A new global gyrofluid code was developed and results were obtained for ITG-driven turbulence in cylindrical and toroidal geometry. An electromagnetic, five-dimensional gyrokinetic code was brought on line in parallel mode, and first simulations of ITG and electron temperature gradient (ETG) turbulence were undertaken (separately). Encouraging agreement with the gyrokinetic flux-tube particle code results have been seen so far for ITG turbulence. Gyrofluid results for toroidal ETG modes have also been confirmed with this code.

Steady progress was made in adding non-adiabatic electron physics and electromagnetic effects to more codes in the NTTP suite. Part of our team has taken a direct approach to comparing turbulence-based theories with experiment. The ITG code (Gryffin) is run to saturation using experimentally measured plasma profiles as input, and the results are compared with both the measured turbulence characteristics and the transport fluxes.

Massively parallel gyrokinetic particle simulations show that the ion thermal transport from electrostatic ITG turbulence depends on ion-ion collisions for representative tokamak core H-mode plasma parameters. The collisionality-dependence of the turbulent transport comes from the neoclassical damping of self-generated zonal flows which regulate the turbulence. The results from our full torus gyrokinetic simulations are consistent with the experimental observation that the collisional dependence of transport is much more pronounced in the enhanced confinement regime where turbulence is expected to be weaker than that of typical L-mode plasmas. Furthermore, the fluctuations and heat transport in these simulations exhibit bursting behavior with a period corresponding to the collisional damping time of poloidal flows. This is consistent with the observation in TFTR core plasmas of a density fluctuation bursting with a period close to the collisional flow damping time calculated from experimental plasma parameters. The extension of field-line following coordinates for global simulations enables full-torus nonlinear simulations with realistic plasma parameters.

A significant accomplishment during the past year was the development of a practical formulation for real tokamak geometry which could be simply incorporated into both gyrokinetic and gyrofluid linear and nonlinear codes. We used the Miller local equilibrium developed at General Atomics, which generalizes the conventional s-alpha infinite aspect ratio circle to a finite aspect ratio, shifted, elongated and triangulated ellipse. The formulation resembles circular geometry with an effective magnetic field when the minor midplane radius is used as a flux surface label.

With our reformulated flux tube gyrofluid code, we mapped out the dependence of ITG turbulent transport and E _ B shear stabilization on elongation. Considerable effort has been devoted to the major development of a continuum full radius gyrokinetic code. The code has real geometry, full electron physics with electromagnetism. As computers become larger, the low-n magnetohydrodynamics limit will be spanned with a full torus mode of operation.

Significance

The NTTP simulations are being used to produce linear and nonlinear calculations of drift-type instabilities in realistic tokamak equlibria, which are leading to a deeper understanding of anomalous transport in current experiments and to improving their performance. This simulation work is providing a basis for reduced transport models that fit current experimental databases and from which it is hoped that performance in future experiments can be reliably predicted and optimized. As controlling the energy transport has significant leverage on the performance, size, and cost of fusion experiments, reliable NTTP simulations can lead to significant cost savings and improved performance in future experiments.

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